Power consumption analysis of different hexapod robot gaits (MTR308-15)

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Abstract: The paper is focused on the power consumption analysis of different gaits of our constructed hexapod robot controlled by different Central Pattern Generator (CPG) models. There are a lot of gait patterns in the literature constructed either by different CPG models or using a series of oscillations with adjustable phase lag. The mentioned models, as well as those proposed in our previous paper are used and compared from the viewpoint of energy demand. In general, power consumption of the constructed hexapod robot is experimentally analyzed based on the current consumption in the applied servo motors, which drive the robot limbs. For this purpose the suitable drivers allowing a simple measurement of electric energy consumption of servo motors are used. The obtained experimental results show different energy demand for different robot gaits. Because power consumption is one of the main operational restrictions imposed on autonomous walking robots, we show that the performed energy efficiency analysis and the choice of the appropriate robot gaits depending on the actual situation can reduce the energy costs.

1. Introduction

From the point of view of engineering applications various kinds of mobile six-legged robots (hexapod robots) are suitable for exploration of unknown, broken and unstable places [1]. The legged robots can go where it is impossible for the wheeled robots, however they require extra effort for their locomotion control. As the electric power is a limited resource in autonomous systems, the power consumption in autonomous walking robots is one of the main operational restrictions. This is why during the last few decades various types of hexapod walking robots (and other multi-legged machines) have been manufactured, modified and analytically/experimentally investigated in order to reduce their energy demand. Energy costs analysis and power consumption optimization in hexapod robots are analyzed in detail, for instance, in papers [2,3]. In paper [2] authors assume that the energetic cost during locomotion is given by the sum of positive mechanical work and the heat energy loss, which is proportional to the square of joint torque. Next, they examined the optimal locomotor robot gait by the energetic cost using computer simulations of simple dynamical model of the analyzed hexapod robot. In turn, in recent paper [3] an energy efficiency analysis (including the effects of the gait patterns and the mechanical structure of the robot) were performed for a hexapod walking robot to reduce these energy costs. In order to meet the power saving demands of the analyzed robot, the appropriate torque distribution algorithm was established with a formulated energy-consumption model. The presented in the mentioned paper numerical results show that the proposed method can be applied for reduction of the energy costs during walking of the robot.

There are also numerous other papers devoted to optimization of the energy demand in the walking robot through adjustment other gait parameters [3]. For instance, in order to optimize (minimize) energy demand, in [4] the author optimized the protraction movement trajectory of the robot leg using a modified version of the gradient descent based optimal algorithm of control. Moreover, in this paper the results of optimization were compared with the observations of protraction of stick insects, and it was concluded that a direct biological imitation of protraction is not energy efficient. In papers [2,5] a simulation model of a two-joint six-legged robot is considered. Energy cost analysis is performed with respect to the stride and stance length, the walking velocities, and duty factor of the wave gaits. The paper [6] is focused on the structural parameter analysis, where the foot force distribution for a six-legged walking machine is obtained for minimum energy consumption over a full cycle for regular wave gaits. In addition, in the mentioned paper geometric work loss for a walking machine with articulated legs is minimized by controlling interaction forces at the foot-ground interface. Minimum energy foot forces are also studied for various duty factors, lateral offsets, link proportions, as well as friction between the ground and the robot leg tip. Authors of the paper [7] proposed an energetic model for walking robots based on dynamic and actuator models, which allows the evaluation of the influence of the leg configuration, body weight, or gait parameters on power consumption. The presented in this paper technique is used to find the optimum stride length for the minimum energy expenditure of a biped prototype depending on the speed and payload, taking into account level and slope walking. Various parameters (defining the trajectories of the robot limb tip) aimed on optimizing energy costs of the robot during walking on non-regular terrain are also tested in paper [8]. In turn, the paper [9] is focused on the analysis of the torque contributions of different dynamic components in real leg trajectories taking into account backlash, friction and elasticity effects in the gear reduction system. The authors of this paper propose a new method to derive the dynamics of a robot leg as a function of parameters of the leg-trajectory. The experimentally found simplified equations of motion reflect the reality of the physical system and can be used in a real-time dynamic-control system.

In this paper experimental investigations regarding an energy consumption of our constructed hexapod robot as the sum of the energy consumed in all of the joints are considered. The DC motors of applied servomechanisms in the joint of the leg are used for obtaining the power consumption experimental data from the required voltage and current values. It should be noted that experimental studies of motor mechanisms are especially challenging - they are characterized by a high degree the task of integrating influences from the surrounding environment. Our investigations involve various trajectories of the robot leg generating via different central pattern generator (CPG) signals, namely

Hopf oscillator, van der Pol oscillator, Rayleigh oscillator, and stick-slip induced vibrations. Both direct and inverse kinematics of the robot leg, as well as the mentioned CPGs are considered in detail in our previous paper [10].

The rest of the paper is organized as follows. First biologically inspiration and constructed prototype of the hexapod robot are briefly introduced. Both direct and inverse kinematics of the hexapod robot leg, as well as chosen oscillators as a CPGs signals are presented based on our previous paper [10]. Next, the experimental stand, including the electronic system for measuring energy consumption (taking experimental data from the voltage and current values of the supply) is briefly described. In result, experimental energy consumptions for the mentioned above CPG signals are compared and discussed. The last section contains conclusions of the performed investigations and possible outlook for future investigations.

2. Prototype of the hexapod robot and modeling of the leg tip movements

Construction of the entire body and its six limbs of our hexapod robot was motivated by the morphology scheme of the stick insect presented in Fig. 1. On the basis of the mentioned morphology scheme we consider first a kinematic model (Fig. 2) and finally construct the prototype of the robot (Fig. 3). All six identical limbs are manufactured by aluminum, whereas as the actuators standard servomechanisms are used and applied. The actuators are independently controlled via Pulse Width Modulation (PWM) technique described in [11]. The most important details of the constructed robot legs are presented in Tab. 1.

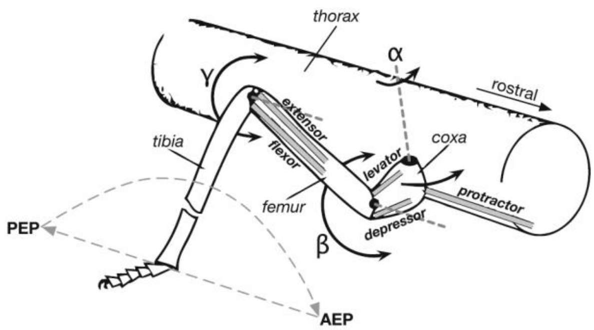


Figure 1. A morphology scheme of a leg of stick insect with coxa (cx), femur (fe) and tibia (ti) as three functional segments. Three mentioned segments are connected through hinge joints: the thorax-coxa joint (α), the coxa-femur joint (β), and femur-tibia joint (γ). The dashed lines denote swing movement and stance movement. PEP (AEP) denotes the posterior (anterior) extreme position, respectively [12].

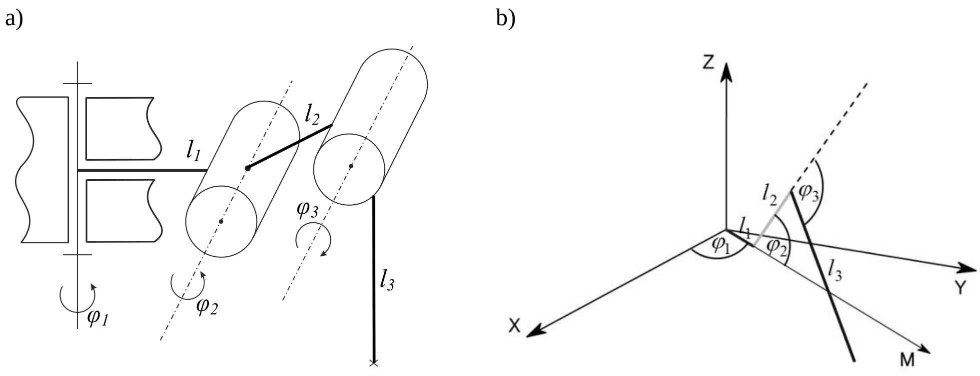


Figure 2. Kinematic structure (a) and location of the hexapod leg in the global base coordinate system (b).

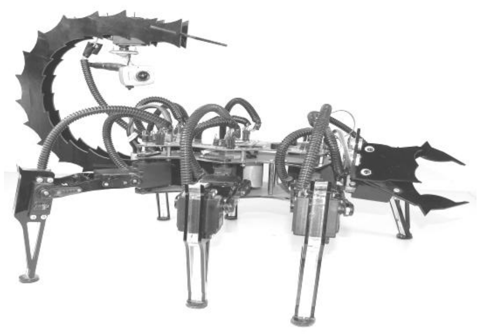


Figure 3. Constructed prototype of the hexapod robot.

Table 1. Parameters of the hexapod robot legs.

Name	Symbol	Value
coxa	l_1	27 mm
femur	l_2	70 mm
tibia	l_3	120 mm
thorax-coxa joint	φ_1	$0 - \pi$
coxa-trochanterofemur joint	φ_2	$-\pi/2 \ldots \pi/2$
femur-tibia	φ_3	$0 \ldots 5\pi/6$

Direct kinematics of the robot leg can be expressed as follows (see [10])

$$\begin{cases} x = \cos\varphi_1(l_1 + l_2\cos\varphi_2 + l_3\cos\varphi_2\cos\varphi_3 + l_3\sin\varphi_2\sin\varphi_3), \\ y = \sin\varphi_1(l_1 + l_2\cos\varphi_2 + l_3\cos\varphi_2\cos\varphi_3 + l_3\sin\varphi_2\sin\varphi_3), \\ z = l_2\sin\varphi_2 - l_3\cos\varphi_2\sin\varphi_3 + l_3\sin\varphi_2\cos\varphi_3, \end{cases} \tag{1}$$

while the inverse kinematics has the form

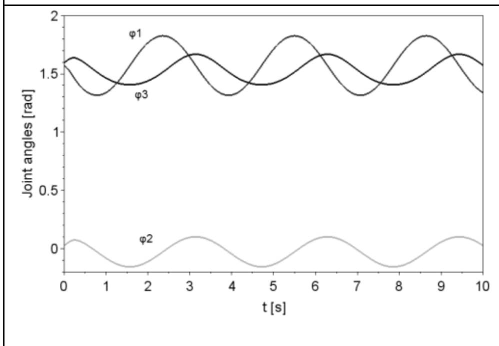
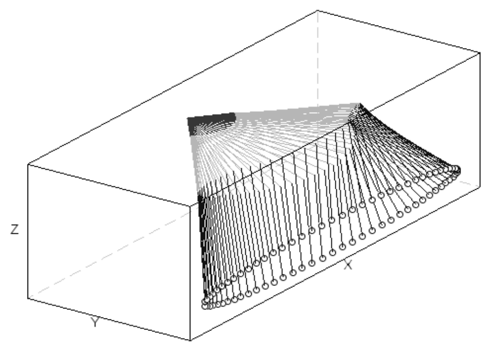
$$\varphi_1 = \begin{cases} \arctan(y/x) & \text{if} \quad x > 0 \\ \pi/2 & \text{if} \quad x = 0 \\ \pi - \arctan(y/(-x)) & \text{if} \quad x < 0 \end{cases}, \quad \varphi_2 = \begin{cases} \alpha + \beta & \text{if} \quad \sqrt{x^2 + y^2} - l_1 \geq 0, \\ \alpha - (\pi - \beta) & \text{if} \quad \sqrt{x^2 + y^2} - l_1 < 0, \end{cases}$$

$$\varphi_3 = \arccos\left(\frac{c^2 - l_2^2 - l_3^2}{2 l_2 l_3}\right), \tag{2}$$

where: $\alpha = \arccos\left(\frac{l_3^2 - l_2^2 - c^2}{-2l_2c}\right)$, $\beta = \arctan\left(\frac{z}{\sqrt{x^2+y^2} - l_1}\right)$ and $c = \sqrt{z^2 + \left(\sqrt{x^2+y^2} - l_1\right)^2}$.

In our studies we use the method to control the hexapod robot's leg by planning out the leg tip trajectory and the velocity for transfer phase and support phase. The shape of the trajectory of the robot leg tip is generated by CPG. The appropriate positions of the phase trajectories of individual points are converted into joint space by the inverse kinematics relationships. The corresponding joint angles finally give a predetermined shape of the trajectory of the robot leg tip by employed direct kinematics. There are numerous models to generate the central oscillation presented in the literature [13]. In our investigations we use four different oscillators, namely: Hopf oscillator, van der Pol oscillator, Rayleigh oscillator and stick-slip oscillator. Both equations and system parameters governing the mentioned oscillators are presented in Tab. 2. Moreover, time series of angles in the appropriate leg joints and trajectories of the robot leg tip are presented in Tab. 2. The presented results are used in our experimental investigations in order to comparison different energy demand for various robots gaits.

Table 2. CPG models applied to the control of the hexapod leg movements, time series of joint angles and leg configurations with the stable trajectory regarding the leg tip of the robot.

<table>
<tr><td colspan="2">a) Hopf oscillator: $\begin{cases} dX/dt = (\mu - X^2 - Z^2)X + \omega Z, \\ dZ/dt = (\mu - X^2 - Z^2)Z - \omega X, \end{cases}$ $\mu = 6$, $\omega = 2$, $X(0) = 0$, $Z(0) = 1$.</td></tr>
<tr><td>
</td><td>
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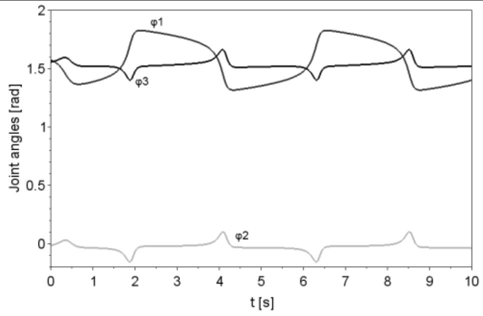
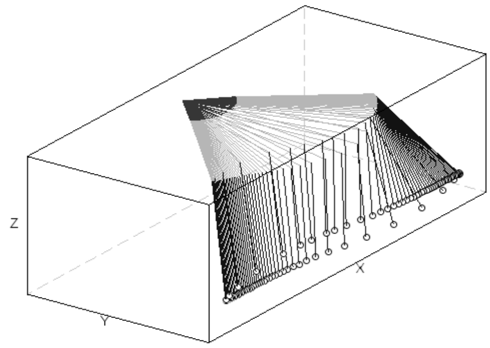
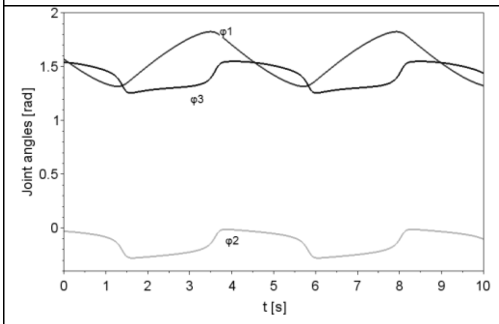
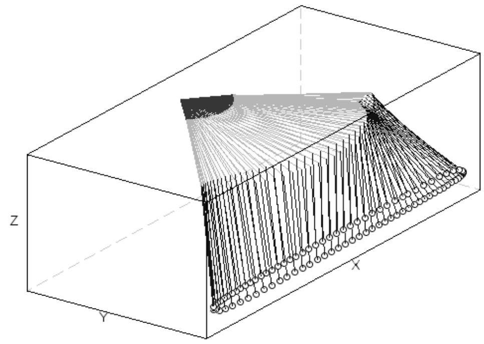
b) van der Pol oscillator: $\begin{cases} dX/dt = Z, \\ dZ/dt = \mu(1-X^2)Z - \omega^2 X, \end{cases}$ $\mu = 6$, $\omega = 2$, $X(0) = 0$, $Z(0) = 1$.





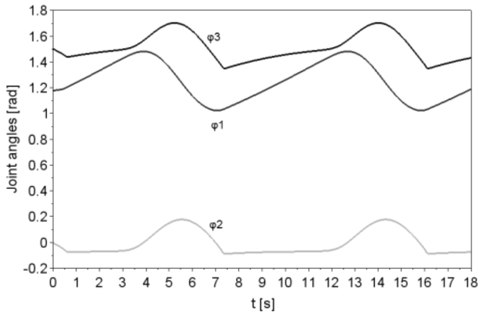
c) Rayleigh oscillator: $\begin{cases} dX/dt = Z, \\ dZ/dt = \mu(1-Z^2)Z - \omega^2 X, \end{cases}$ $\mu = 6$, $\omega = 2$, $X(0) = 0$, $Z(0) = 1$.

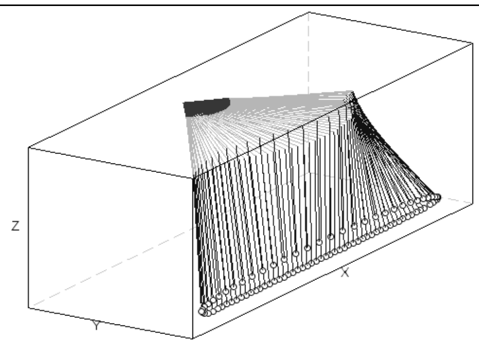




d) Stick-slip oscillator: $\begin{cases} dX/dt = Z, \\ dZ/dt = -d_c Z - X + F_{fr}(v_r), \end{cases}$ $d_c = 0{,}01$, $F_{fr}(v_r) = \dfrac{F_s}{1+\delta\,|v_r|}\tanh\left(\dfrac{v_r}{\varepsilon}\right)$,

$v_r = v_{dr} - Z$, $F_s = 1$, $\delta = 3$, $v_{dr} = 0.5$, $\varepsilon = 10^{-2}$, $X(0) = 0$, $Z(0) = 0$.





3. Experimental results

Power electric energy demand in servomechanisms of the robot has been performer using computer program created in LabView environment. Figures 4-7 show time series of angular positions and electric power consumption of the appropriate servomechanisms of single hexapod leg. Experimental results are performed for four mentioned earlier different CPG models, namely: Hopf oscillator, van der Pol oscillator, Rayleigh oscillator, as well as stick-slip oscillator. In all cases the stride length of the robot and number of stride lengths are the same. During experimental measurement the obtained total length of the road is 80 cm during time equal 22 s.

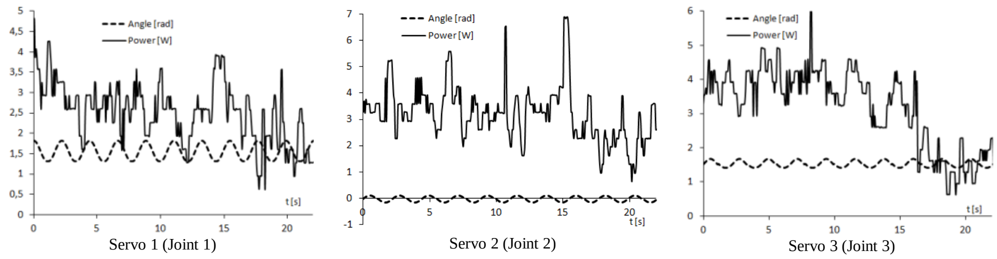


Figure 4. Power consumption analysis of the hexapod movement generated via Hopf oscillator.

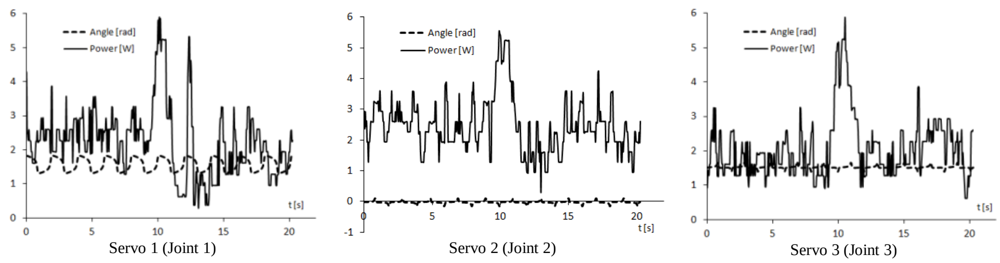


Figure 5. Power consumption analysis of the hexapod movement generated via van der Pol oscillator.

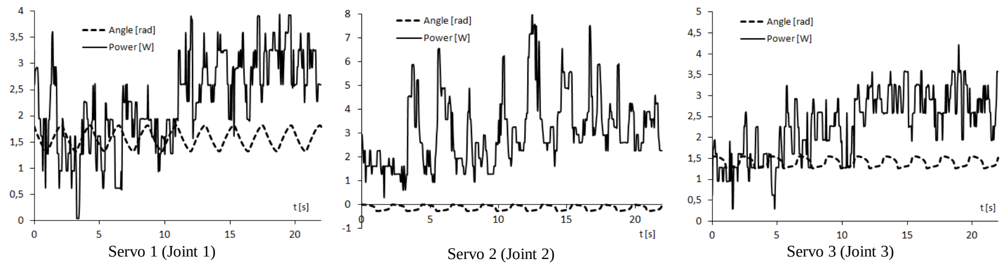


Figure 6. Power consumption analysis of the hexapod movement generated via Rayleigh oscillator.

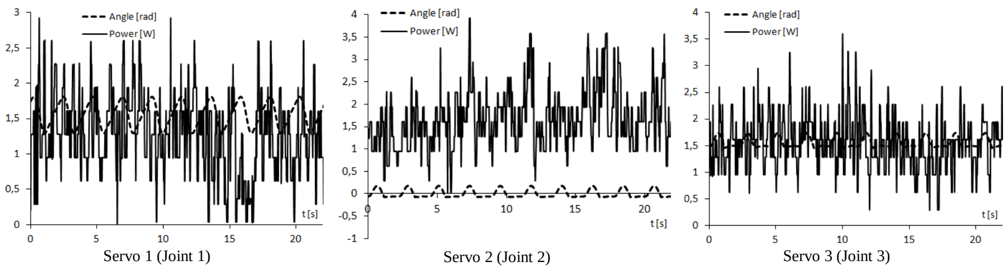


Figure 7. Power consumption analysis of the hexapod movement generated via stick-slip oscillator.

A comparison of the total energy demand of all servomechanisms of the robot, which obtain the same road length in the same time using different CPG models, are presented in Fig. 8.

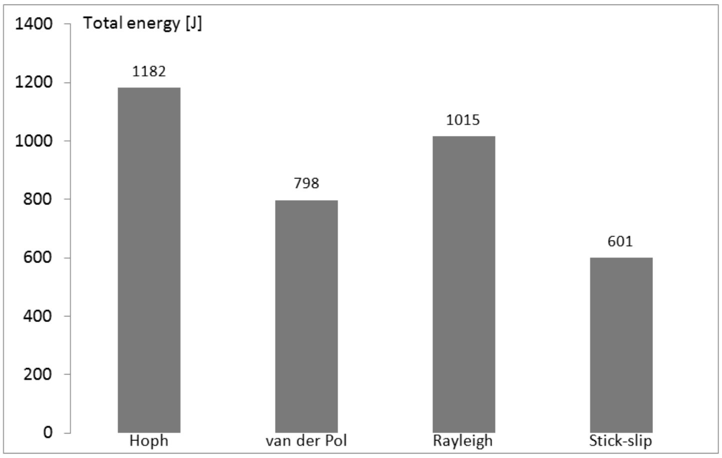


Figure 8. Comparison of the total energy demand of the hexapod robot for different CPG models.

4. Conclusions

In this paper the power consumption analysis of different gaits of our constructed hexapod robot controlled by different CPG models is experimentally investigated. Although there are a lot of gait patterns in the literature constructed via different CPG models, in our investigations we consider three well known CPG models (Hopf, van der Pol and Rayleigh oscillators), as well as proposed in our previous paper CPG model (mechanical stick-slip oscillator). In order to compare electric energy consumption of the robot for various gaits (based on the electric current consumption in all hexapod servo motors), the appropriate electronic and computer system is proposed and used. The relatively simple experimental measurements of electric power consumption show different energy demand for different robot gaits. Investigations of motor mechanisms are especially challenging because they are characterized by a high degree the task of integrating influences from the environment. As can be seen, from the energy demand point of view the proposed mechanical stick-slip CPG model is more efficient in comparison to other applied CPG models. In this CPG model in the stance movement the distance between the leg tip of the robot and center of the robot coordinate system positioned on the body of the robot at the point of attachment leg is constant. This is a result of keeping the center of gravity of the robot at a constant level, and finally the servo motors placed in leg joints robot do not have to perform extra electric energy, which significantly decreases the energy demand. It should be noted, that the development of multi-legged robots was always restricted by the problem of their high power consumption. This is why the proposed movements of the legs of the hexapod robot can be used to overcome long distances, particularly in the regular terrains in a more efficient way. Power efficiency optimization is this field without improving the power supply unit allow to increase of mission time of the robot.

Acknowledgments

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